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Measuring the Interference at an RFID Tag: Where Does It Have an Impact?

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Abstract—In this paper we consider reader collisions in an Radio Frequency Identification (RFID) system, especially how interference impacts the ability of a passive UHF tag to respond. We propose two innovative applications for using interference: 1) Blocking a tag response, and 2) cooperative reading of a tag. In order to investigate their applicability we focus on the experimental evaluation, where we impose interference on the download and uplink, respectively, and on both links simultaneously. The results are positive with respect to blocking the tag, where modulated Co-Channel Interference (CCI) shows most effective. Based on the measurements it is however not possible to read a tag cooperatively, i.e. the tag is unable to utilize the interference as an additional energy source.

I. INTRODUCTION

Today's Radio Frequency Identification (RFID) is primarily utilized as a tool for identification in supply chain management services. But in recent years the RFID technology has received great attention, [1], as RFID has the potential of becoming ubiquitous, and it is therefore considered a key technology for pervasive networks and services [2]. Such widespread use of RFID systems to provide accurate identification of all tagged objects, requires a dense deployment of RFID readers, introducing collisions as the readers interfere with each other.

The read range of a reader is significantly shorter than the interference range. Hence, when considering reader collisions they cover two different collisions: 1) Reader-tag collision, where a tag is located within the read range of multiple readers. The reader signals interfere with each other, making it challenging for the tag to decode as much as just a single reader request, not impossible though. 2) Reader-reader collision, where a reader signal interferes with the reception of a tag response at an adjacent reader. This can occur when readers are sufficiently spaced so their interrogation zones do not overlap, but their interference range reach into interrogation zones of adjacent readers. The EPC Global C1 Gen 2 standard [3] implements a dense-reader-mode, allowing densely deployed readers to operate simultaneously in separate frequency bands. Modern readers then implements filters that can separate frequency bands and hereby filter out the main part of the interference. However, tags do not have this option, and are thus forced to cope with the interfered signal.

In this paper we investigate the impact of reader collisions under different types of interference in order to map in which conditions a tag can be read. Basically the communication between reader and tag can be interfered in the following transmission periods:

a) The reader-to-tag commands

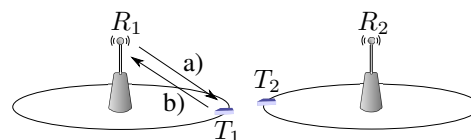


Fig. 1. The interrogation zones of readers R_1 and R_2 , with the tags T_1 and T_2 , respectively. The area between the zones is the buffer zones where the readers have low probability of reading tags. The arrows a) and b) denotes the transmission of the commands from reader to the tags, and the response from tag to reader, respectively.

- b) The tag-to-reader reply
- c) During both periods

The reader and tag represents two different levels of complexity, and is therefore expected to have different susceptibility to interference. Hence, in this paper we consider each of the periods above separately, and investigate the impact of interference on the tags readability.

As an example consider Fig. 1, a scenario with two readers, R_1 and R_2 , and two tags, T_1 and T_2 , with the transmissions a) and b) illustrated by arrows. The probability of reading a tag decreases with the distance between reader and tag. In Fig. 1 the tags are located on the edge of the interrogation zones, and will therefore be read with decreased probability. Outside the zones a tag may still be read, but with low probability. The readers operation causes mutual interference, hence they are deployed with a certain separation, often referred to as the buffer zone. By clarifying the impact of a), b) and c) we enable a constructive utilization, in contrast to the normal destructive perception, of interference. We thus propose two innovative applications for using interference constructively in an RFID system:

- 1) Blocking a tag response, i.e. preventing tags from sending replies. This can be used to block tags for security purposes, or mitigate the problem of false positives. In Fig. 1, this means that by letting R_2 interfere the operation of R_1 , we can prevent T_2 in responding to R_1 and cause a false positive reading, which again enables a closer deployment of readers and their interrogation zones.
- 2) Foster cooperative reading of tags. While interference is harmful for reception, it can be seen as an additional RF power available to be harvested by the tag and thus help the tag to get its response through. This means that the interference from R_2 helps energizing T_1 , so it with high probability can respond to R_1 , i.e. the range of R_1 is effectively increased due to the interference from R_2 .

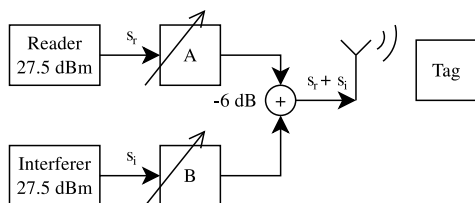


Fig. 2. Signal flow diagram of the setup used in this work.

Immense work have been published in the area of reader collision already, proposing different methods to utilize the dense-reader-mode and optimize for low probability of reader collision. In [4], [5] the problem of reader collision is thoroughly described and existing methods to cope with this problem are surveyed. An example is [6], where reader collisions are described as a graph coloring problem, in order to derive a suited reuse distance between the frequency channels in RFID dense-reader-mode. Alternatively [7] suggests using an algorithm similar to the Q-algorithm, from the Gen 2 standard, as MAC protocol for the network of readers. Most recently [8], [9] presents schemes to dynamically adapt modulation depth and transmission power, respectively, to avoid reader collisions. Moreover, in [10], [11] it has been investigated what level of interference will cause a tag not be identified by the reader.

The approaches above presents intelligent methods to avoid reader collision in general, not differing between reader-reader collision and reader-tag collision. This paper considers both collision types separately. Moreover, we present the experimental investigation of the applicability of using interference to enable blocking of passive tags and cooperatively power up and read the tags.

The remainder of this paper is structured as follows; In section II the system model and the experimental setup are described. The obtained results are presented in section III and in section IV the results are discussed and final conclusions are drawn.

II. SYSTEM MODEL AND EXPERIMENTAL SETUP

In this work we are considering a scenario where multiple readers are deployed to cover the entire space. Note that the term reader refers to the apparatus that can read tags in its proximity, i.e. in practice, this can refer to an RFID reader including an antenna, or just an antenna attached to a reader located elsewhere. We define an interrogation zone as the area around the reader where a tag is read with high probability ($> 99\%$).

To investigate the impact of interference in this scenario we have constructed a setup, where distances are introduced artificially using signal attenuators. In Fig. 2 this setup is illustrated with a signal flowchart.

The reader and interference signals are denoted s_r and s_i respectively, and the blocks labeled A and B are adjustable attenuators. It should be noted, experiments have shown that due to a lossy wireless coupling to the tag, the reader is unable

to read the tag if A attenuates the signal more than 12 dB. Using A and B the signal range, or the theoretical distance, can be adjusted from the interrogating and interfering reader to the tag, respectively. The utilized interrogation power is 30 dBm, which is the maximum power allowed in Europe. But due to connectors and cables in the signal path, we have a fixed attenuation of 2.5 dBm, and the combining element has an internal attenuation of 6 dB. This means that the maximum power delivered by either the interrogating or the interfering reader is 21.5 dBm. The resulting Signal to Interference Ratio (SIR) is then given by the difference between A and B :

$$SIR = B - A \quad [\text{dB}] \quad (1)$$

Basically the interferer could represent any nearby source using the Ultra High Frequency (UHF) band, but in this work we focus on densely deployed RFID systems, where the interference will come from an adjacent reader. An interfering reader shifts between transmitting commands, using an amplitude modulated carrier wave, and listening for tag responses while continuously transmitting the unmodulated carrier wave to energize tags. To investigate both situations s_i then needs to be modeled with and without amplitude modulation.

The dense-reader-mode specified in the EPC Global Gen2 standard [3], enable readers to use four different frequency bands, in order to decrease the interference between them. Moreover, the tags uses two sub-carriers, so their response lies in the side bands to the readers carrier frequency, as this helps the reader to filter out adjacent and co-channel interference. Hence to represent an RFID system in dense-reader-mode, s_i should have center frequencies corresponding to the different channels in the available frequency band.

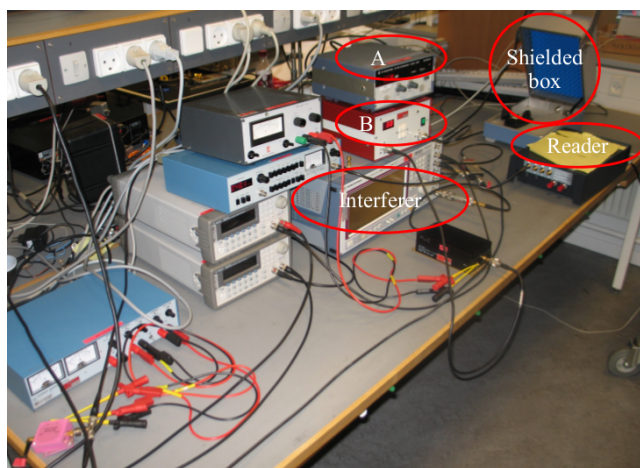
The reader available in this work, an Intermec IF5, does not support the dense-reader-mode. Tags will therefore respond using the same carrier frequency as the interrogating reader, making Co-Channel Interference (CCI) particularly harmful in this setup. However, this does not mean that the experimental results obtained in this work cannot be compared to RFID systems operating in dense-reader-mode. Imposing Adjacent-Channel Interference (ACI), whether dense or single reader mode is utilized, will have similar effect on both a tags ability to correctly receive the reader commands and a readers ability to receive the tag response. Only CCI is different, as in this work the interrogating reader will share the band with both interference and the tag.

A. Notation

To ease descriptions and explanations we introduce the following notation when addressing events:

T :	Tag received Query from reader
R :	Reader received tag response successfully
I_R :	Interference imposed during Query from the reader
I_T :	Interference imposed during tag response
Z :	The tag is located inside the interrogation round

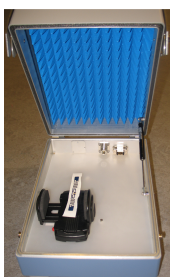
TABLE I
SPECIFICATION OF EVENTS IN THE EXPERIMENTS.



(a) The experimental setup.



(b) The utilized passive UHF tag. with the coupling element (black) and the tag.



(d) Closed box.

Fig. 3. The utilized experimental setup, with closeup pictures of the tag and the shielded box.

The inverse of an event is denoted with a bar, e.g. \bar{T} refers to the event that a tag did not successfully receive the *Query* command from the reader. We can then reuse the notation from probability theory to precisely describe a scenario. As an example the probability of reading the tag response given that the tag received the *Query* and its response is not interfered can be specified by $P(R|T, \bar{I}_T)$. If the tag is located inside the interrogation zone this probability is $> 99\%$, i.e. $P(R|T, \bar{I}_T, Z) \approx 1$.

III. RESULTS

To investigate the susceptibility of an RFID system to interference, we have constructed an experimental setup based on the flow chart from Fig. 2. An elaborate flow chart is described in appendix B. Pictures of the resulting setup is shown in Fig. 3. Pictures of the resulting setup is shown in Fig. 3, where the tag is placed inside a shielded box, see Fig. 3(c), to shield the tag from multi-path effects in the lab.

We will investigate both the reader-tag and the reader-reader collisions respectively, and the measurement procedures are presented in the following along with the results for each collision type.

A. Reader-Tag Collision

When investigating collisions at the tag, we are interested in the ability to receive and interpret the reader commands under interference. It is complex in practice to sniff the reception directly on the tag, since a connected probe would change the reception parameters of the tag significantly. [12] Instead we utilize that a tag requires to successfully receive the *Preamble* + *Select* + *Query* commands [3] in order to respond. In this experimental setup it is therefore only required to switch on the interferer during the initiation of the interrogation round, leaving the tag response undistorted. Given that the uplink channel from tag to reader is error less, any failed readings can be ascribed to the tags ability to receive the reader commands. This requires the tag to be located inside the interrogation zone, in a distance where a good read rate, $> 99\%$, can be maintained. The events from Table I can be used to summarize the setup:

I_R :	Interference imposed during <i>Query</i> from the reader
\bar{I}_T :	Interference switched off during tag response
Z :	The tag is located inside the interrogation round

Given that $P(R|T, \bar{I}_T, Z) \approx 1$, the probability that the tag successfully receives the reader commands can be written as $P(R|I_R, \bar{I}_T, Z)$.

For ACI a frequency distance of one and two channel widths have been utilized. In this way the importance of frequency separation to the tag and to the reader, respectively, will be evident from the measurements. To have the tag located inside the interrogation zone we use the attenuation $A = 4$ dB. This attenuation has been experimentally identified, and is relatively low due to a loss in the coupling element in the shielded box, see Fig. 3(c), of approximately 20 dB.

The interference power is then stepwise increased by decreasing the attenuation B . For each SIR value, the reader initiates n interrogation rounds with a frame size of 1, and based on the number of successful responses the response probability, $P(R|I_R, \bar{I}_T, Z)$, is calculated. The required size of n , for the response probability to be statistically significant is investigated in appendix A. Table II summarizes the parameters used in this setup, and in Fig. 4 the resulting $P(R|I_R, \bar{I}_T, Z)$ is plotted as a function of SIR. From the plots we see that in general a high SIR is required to maintain a good response rate, and that CCI provides both the best and the worst tag performance. The former is surprising since CCI was expected to be the most harmful type of interference. The

Samples (n):	500
Reader:	Intermec IF5
Reader carrier wave (f_c):	866.5 MHz
ACI #1 (f_{ci1}):	867 MHz
ACI #2 (f_{ci2}):	867.5 MHz
Tag:	Alien, ALN9640 (Passive, UHF)
Tag cardinality:	1

TABLE II
LIST OF PARAMETERS.

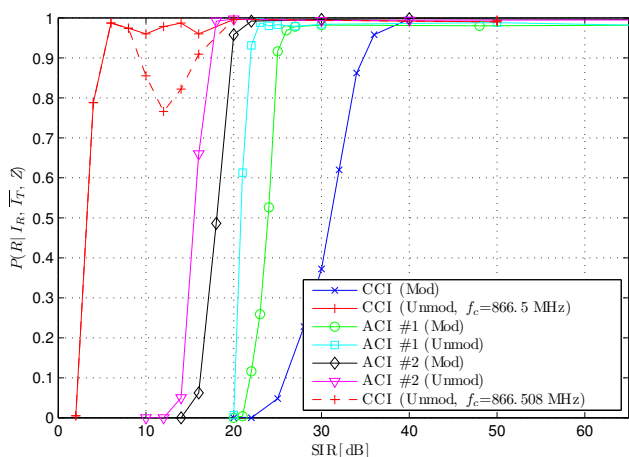


Fig. 4. The response probability of a tag when reader commands are subject to interference, both Co-Channel Interference (CCI) and Adjacent-Channel Interference (ACI).

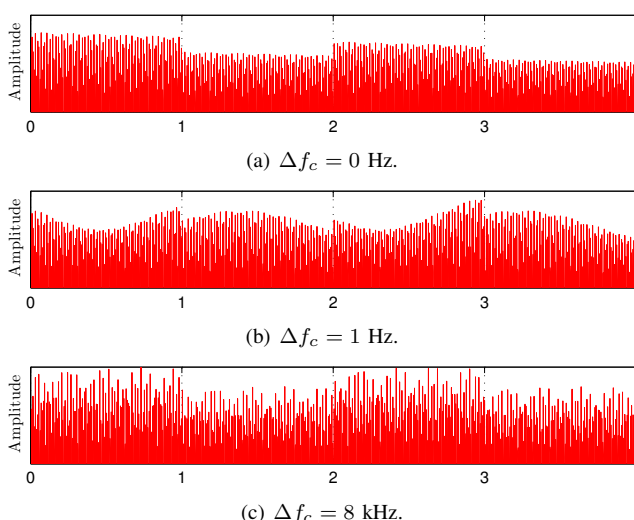


Fig. 5. An example of a 866.5 MHz carrier wave modulated with a square wave plus interference, where amplitude is plotted as function of bit times. The interference has a small difference in phase and a frequency difference of 0 Hz in Fig. 5(a), 1 Hz in Fig. 5(b) and 8 kHz in Fig. 5(c).

explanation to why unmodulated CCI is less harmful may be that it mainly contribute with a decrease in modulation index, hence unmodulated CCI might help energize the tag.

During the measurements for CCI, with $f_c = 866.5$ MHz, we experienced an unmotivated dip in response probability at an SIR of 8 – 20 dB. It was observed that increasing f_c to 866.508 MHz did not give the same dip in performance. This is due to the unsynchronized operation of the reader and interferer, where a small difference in carrier frequency, Δf_c , can occur. This difference causes the resulting amplitude of the interfered signal to vary according to Δf_c , as illustrated in Fig. 5. In Fig. 5(a) where $\Delta f_c = 0$ Hz, the AM modulation is relatively simple to deduce from the resulting signal. The same is the case when Δf_c is high, see Fig. 5(c), as the interference just causes a fast ripple on the levels in the AM

modulated reader signal. However, if Δf_c is only a few Hz, Fig. 5(b), the periods in amplitude variation are similar to the length of a symbol transmitted from the reader. In this case it becomes difficult to determine the high and low levels of the AM modulation, which significantly decreases the probability of decoding the reader commands at the tag.

It was expected that a modulated interferer would have a greater impact on the tag than an unmodulated. However, if we consider a response rate of 99 %, we see a difference of ≈ 10 dB between modulated CCI and modulated ACI #1. Since the tag does not come with any internal frequency filtering this is a quite unexpected result. The utilized tag is targeted for global use, and operational in the frequency band from 860 – 960 MHz covering both the American, European and Asian bands for UHF RFID. Hence, the tag is expected to have constant performance in the relative small frequency band utilized in these experiments. Instead the explanation to the 10 dB difference is considered to be the frequency difference, Δf_c . Modulated interference has, as expected, the most significant impact on the tags ability to respond, but as the frequency distance between the reader and interferer signals increase, the interference has less impact. In this way interference from adjacent channels introduces a fast ripple of the reader signal, as illustrated in Fig. 5(c), where the modulation introduces a small, but constant, impairment of the tags ability to respond.

From this measurement, the main result that can be concluded is that by imposing interference, it is possible to keep a tag, that otherwise would respond, from responding.

B. Reader-Reader Collision

The collisions at the reader are investigated by repeating the experiment for reader-tag collision, but where the interference is absent in the initiation of the interrogation round, and instead present while the tag responds. The tag is assumed to remain inside the interrogation zone, $A = 4$ dB. In this way the tag will successfully receive the reader commands, and the interference made to the incoming tag response can be isolated as the only source for rendering the reader unable to receive the tag response. This setup can be summarized by the following events:

- $\overline{I_R}$: Interference switched off during *Query* from the reader
- I_T : Interference imposed during tag response
- Z : The tag is located inside the interrogation round

The probability of the tag successfully receives the reader commands is then denoted $P(R|\overline{I_R}, I_T, Z)$, and is plotted in Fig. 6 with solid lines, as a function of the SIR. Note that the dashed lines in Fig. 6 are the probability of the tag responding under interference, $P(R|I_R, \overline{I_T}, Z)$, repeated from Fig. 4 for comparison. Considering only the plots for reader-reader collision, we see that the ACI leaves the system in much better conditions to receive the tag reply, as expected. In all examples there is a very small but constant difference between modulated and unmodulated interference, where the modulated interference is most harmful. The plots of $P(R|\overline{I_R}, I_T, Z)$

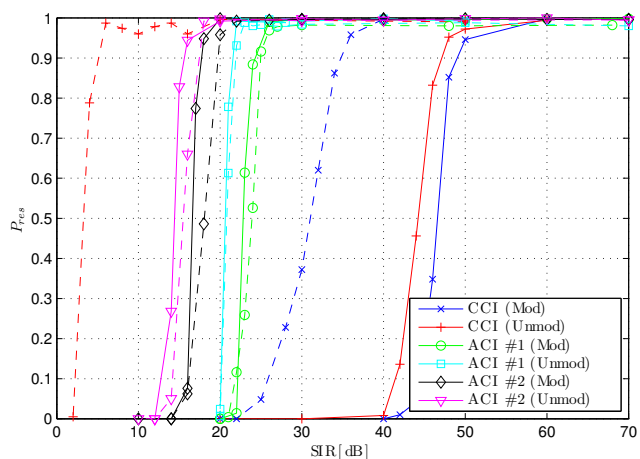


Fig. 6. $P(R|\overline{I_R}, I_T, Z)$ (solid lines) and $P(R|I_R, \overline{I_T}, Z)$ (dashed lines) plotted as a function of the SIR.

under CCI and under ACI #1 are horizontally shifted approximately 25 dB. This means that a 25 dB better signal is required in case of CCI. At the reader side it is possible to improve the reception capabilities by increasing the receiver complexity, hence this great performance difference is unexpected. For a reader supporting dense-reader-mode however, we would expect a better performance under CCI, as the tag replies in the side bands.

If we compare the read probabilities for reader-tag and reader-reader collisions, we see that for ACI they require approximately the same SIR conditions to maintain a high read rate. The small difference partly represents the imprecision in the measurements and partly the probability of the reader being unable to decode the tag reply.

Under CCI we see a significant difference between reader-reader and reader-tag collisions. The tag is able to reply under an interference level around 15 dB higher than the SIR level a reader is able to receive the reply in. Here we see the effect of the channel filters in the reader, because, for CCI, the reader is unable to filter out the interference, hence the tag response disappears in the interference. It does not matter whether the interferer is unmodulated, since the two carriers are not synchronized. However, for unmodulated CCI the tag is able to respond even with very low SIR. This could indicate that with unmodulated CCI it is possible to help power up the tag, and in this case increase the communication range between reader and tag.

C. Continuous Interference

Finally the collision experiment is repeated using a continuous interferer, where interference is transmitted during the entire interrogation round:

- I_R : Interference switched off during *Query* from the reader
- I_T : Interference imposed during tag response
- Z : The tag is located inside the interrogation round

In Fig. 7 the measured $P(R|I_R, I_T, Z)$ is plotted, as a function of the SIR. $P(R|I_R, I_T, Z)$ represents the per-

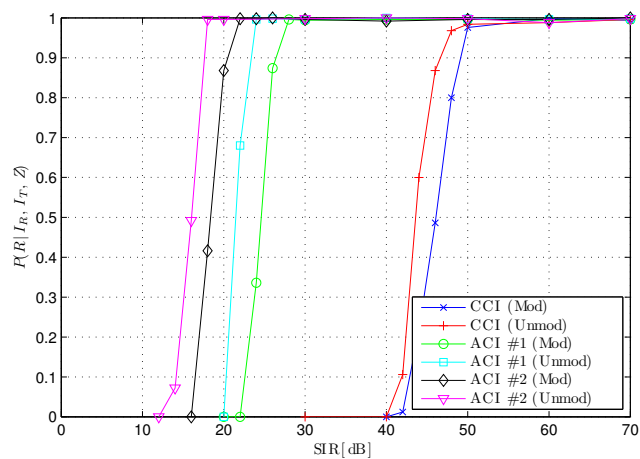


Fig. 7. The probability of power up and read the tag under interference.

formance when both reader-tag and reader-reader collisions are taken into account. If we compare $P(R|I_R, I_T, Z)$ and $P(R|\overline{I_R}, I_T, Z)$, from Fig. 7 and 6 respectively, the performance under ACI is similar, but under CCI the resulting performance is limited by the readers ability to extract the tag response from the interfered signal. This is a special case, as the utilized reader is not operating in dense-reader-mode. These results are therefore not representative to the performance under CCI in dense-reader-mode, where the tags replies using sub-carriers enabling a reader to filter out a co-channel interferer.

D. Interference As Power Source

It is desired to test whether interference, in form of an unmodulated carrier wave, from an adjacent reader can aid the communication between reader and tag. To realize this, we consider the case where a tag is located in the intermediate zone between two readers, the buffer zone, where a reader has low probability of reading the tag. We choose $A = 8$ dB where $P(R|\overline{I_R}, \overline{I_T}, \overline{Z}) = 31\%$. From Fig. 4 and 6 we saw that the ability to read a tag changes from ≈ 1 to 0 in a matter of a few dB SIR. With $P(R|\overline{I_R}, \overline{I_T}, \overline{Z}) = 31\%$ we are therefore focusing on a point on that very steep flank. This means that small changes in the read conditions may cause large changes in read probability. To mitigate this effect we increase the number of samples, n , to 1000.

Passive tags requires a carrier wave to constantly beam power to them in order to operate, the unmodulated interference is therefore continuous in the entire interrogation round. It should be noted that in this experiment the interference is not synchronized to the carrier wave from the reader. The resulting $P(R|I_R, I_T, \overline{Z})$ is measured for gradually increasing interference power, and plotted in Fig. 8. The dashed line indicates the reading probability when the interferer is switched off. For both CCI and ACI the read probability is fluctuating significantly, even though n is increased, and none exceeds the probability when interference is absent. It is therefore evident, that in this setup, it is not possible to cooperatively energize

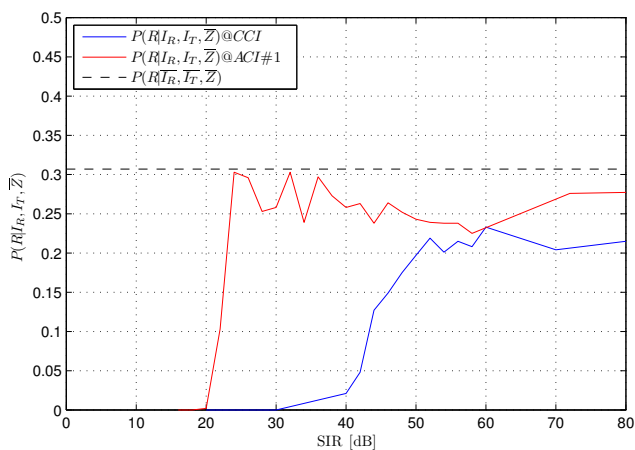


Fig. 8. Probability of reading tag under constant interference versus only interfering the initiating commands from the reader.

a tag. Being unsynchronized the reader and interferer signals collide at random. If it had been possible to synchronize the signals and hereby forcing them to interfere constructively at the tag we might have seen different results. Moreover, a steep decrease in $P(R|I_R, I_T, \bar{Z})$ is visible around SIRs similar to those shown in Fig. 7, since at this interference power, the reader is unable to separate the signals.

IV. DISCUSSION AND CONCLUSION

Interference is traditionally considered a limiting constraint with destructive impact on performance. In this paper we consider interference in Radio Frequency IDentification (RFID) systems, where we investigate its impact, and whether interference has some constructive applications. In particular two applications are considered; 1) Blocking of tag responses, so tags located in a certain area will not respond to an interrogating reader, and 2) Cooperative reading of tags, where interference helps an interrogating reader to energize tags, allowing them to respond.

The experimental results show that by imposing interference on the communication between tag and reader, we can abstain a tag from responding. This is in line with the general perception, seeing interference as a limitation. To keep the tag from receiving the reader commands the type of interference showed important. Using modulated interference in the same channel as the reader requires the least interference power to block the tag. This is preferable as low interference power also keeps the interference towards adjacent readers low. The ability to block a tag effectively makes the probability of a tag responding decrease faster with distance to the reader. This gives a sharper separation between adjacent interrogation zones and reduces the probability of false positive readings of tags, located in the buffer zone between interrogation zones, or in an adjacent zone. Alternatively, it enables a closer deployment of interrogation zones maintaining the same probability of false positive readings.

Using interference to help energize a tag showed however ineffective. From our experiments we saw no indication that

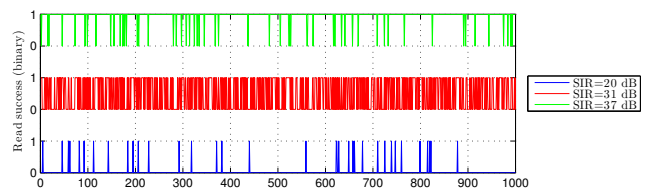


Fig. 9. 1000 reading samples, where a successful read is denoted 1, otherwise 0.

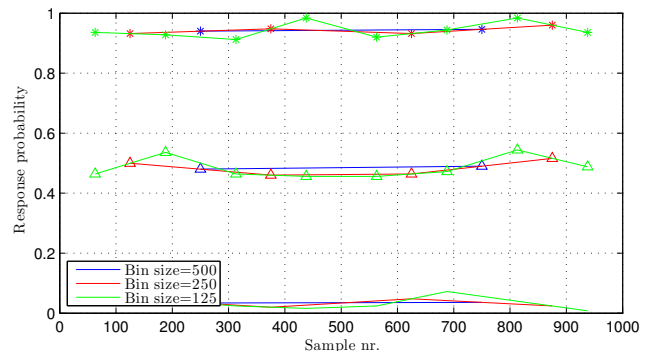


Fig. 10. Response probability as a function of the binned samples. The marker '*' refer to a SIR of 37 dB, 'Δ' a SIR of 31 dB and 'no marker' to a SIR of 20 dB.

interference, in the form of an unmodulated carrier wave, could improve the probability of reading a tag located in the buffer zone. However, using interference synchronized to the readers carrier wave may prove more effective.

It can therefore be concluded that in the utilized setup the interference solely have a limiting impact on the probability of reading tags in RFID systems. An innovative use of this effect, where tag responses are intentionally blocked, is proposed in this paper. In future works we plan to investigate in greater details the potential of blocking tags, with the intention of reducing false positive readings.

APPENDIX A

CHOOSING THE NUMBER OF SAMPLES

The number of samples used to calculate the probability of a tag responding should be chosen such that the response probability is statistically significant. As an example three measurements of modulated CCI have been made, with $n = 1000$ samples and SIR of 20 dB, 31 dB and 37 dB, respectively. In Fig. 9 the results are plotted as binary values: 1 if the tag were read, and 0 otherwise. Tests for randomness using Matlab showed that these reading errors does not come in bursts, but appear at random throughout the entire measurement. To determine a suitable size of n , we split the 1000 samples into bins of 500, 250 and 125 samples, respectively, and plot the response probability for each bin in Fig. 10. For small n we see that the probability is changing significantly from bin to bin, but settles as n increases. For a bin size of 500 the probability only variates a few percent between the two bins. This is sufficient precision when considering that the response probability changes from ≈ 1 to 0 over a few dB in SIR, see

Fig. 4 and 6. Hence, $n = 500$ is utilized when measuring the two types of reader collisions.

APPENDIX B DETAILED FLOWCHART OF SETUP

In Fig. 11 the interferer from Fig. 2 is exploded, with each element described. When the reader initiates an interrogation round it starts by transmitting the unmodulated carrier wave a small period of time to power up the tag, before transmitting the `Preamble + Select + Query` commands. This period is not constant, hence the logarithmic amplifier is used to detect the amplitude modulation from the reader commands. We use this signal to trig waveform generator X to make pulses with a period corresponding to a bit-length, i.e. $80 \mu s$. The first of the pulses from X then trigs waveform generator Y . The starting voltage level of Y depends on the events I_R and I_T , i.e. whether the initiation of the interrogation round or the tag response should be interfered. For I_R Y starts high, and for I_T Y starts low. When triggered Y changes state after a delay of 2.760 ms. This delay corresponds to the duration from the first bit of the `preamble` to the last bit of the `Query`.

The interfering carrier wave is created by the signal generator SMP22, and is triggered by the high level of Y . To modulate the carrier wave we add a sinusoid with a frequency similar to the bit rate of the reader commands. Finally the interfering signal is amplified to match the level of the reader signal before entering the adjustable attenuators A and B . Before being transmitted to the tag the reader and interferer signals are combined.

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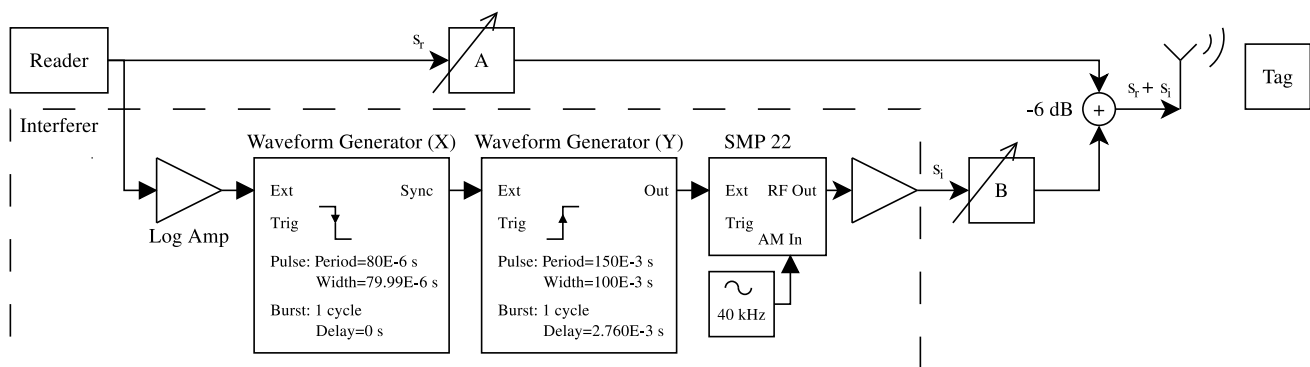


Fig. 11. Detailed signal flow diagram of the setup used in this work.